BELLCOMM, INC.
1100 Seventeenth Street, N.W. Washington, D.C. 20036

SUBJECT: On the Question of Artificial Gravity. Case 710.

DATE: August 23, 1968

FROM: A. N. Kontaratos

ABSTRACT

Potential benefits derived from rotating space systems lie primarily in the realm of improving habitability and maintaining physical fitness. Disadvantages include a tendency of free-falling objects to follow "non-vertical" trajectories, changes in body weight and body-posture during translation, differences between head and foot acceleration and generation of Coriolis forces possibly affecting postural reflexes, locomotion and manual tasks. On the basis of present day knowledge, it appears that a gravity level of at least 0.3 g is suitable for habitability and that an angular velocity of not higher than 6 rpm is physiologically acceptable. Both ground-based and in-flight research activities required to optimize these and other limits are indicated.

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MEMORANDUM FOR FILE

I. INTRODUCTION

The creation of an artificial gravity environment in manned space flight systems appears beneficial for two reasons. From the habitability standpoint, astronaut activities would be greatly simplified. For example, assembly and repair, traction and locomotion, eating and drinking, micturition and defecation are all facilitated by the presence of an inertial directing force. Sanitation will also be easier to maintain if dirt and fluids collect on the floor and circulation of space cabin atmospheres will be better controlled if convection currents exist.

From the biomedical standpoint, benefits derived would lie primarily in the realm of maintaining physical fitness. For example, cardiovascular deconditioning could be delayed, musculoskeletal degradation could be suppressed, and otolithic disorders could be prevented. To date, however, there exists no flight evidence indicating that man will not be able to endure prolonged space flight or perform satisfactorily under conditions of weightlessness. In fact, any apprehension is based not on man's ability to survive weightlessness but rather on his ability to cope with reentry stresses and post-landing normal Earth conditions. Consequently, artificial gravity cannot be justified solely as a physiological support requirement.

Presently three modes of obtaining artificial gravity are being considered--onboard centrifuges, spacecraft spinning and tethered rotation. An onboard centrifuge could be used as a research tool and as a physiological reconditioning device to aid astronaut rehabilitation following prolonged exposure to weightlessness. As a habitability aid, however, the onboard centrifuge is of limited value. Spacecraft spinning or tethered rotation, on the other hand, could be effective from a habitability standpoint and could help delay physiological deconditioning. Both modes, however, interfere with scientific experiments in astronomy and earth applications demanding either non-rotating platforms or accessory experimental modules.

II. UNDESIRABLE ASPECTS OF ARTIFICIAL GRAVITY

Artificial gravity can be readily obtained by creating a centrifugal force. This approach, practical as it may seem, raises, however, the following problems which are further complicated if angular velocity varies and/or vehicle instabilities occur:

1. Free-falling objects viewed by an observer within a rotating space station will follow a path which does not coincide with the local vertical (radius of rotation). Objects will fall in a non-perpendicular trajectory and will land behind their expected impact point by a distance
$$d = R\left[\frac{\sqrt{h(2R-h)}}{R-h} - \cos^{-1}\left(\frac{R-h}{R}\right)\right] *$$
measured opposite to the direction of rotation (h is the height of fall and R is the radius of rotation at floor level).

2. Body weight is not always constant. An astronaut walking along the periphery of the spacecraft and in the direction of rotation will experience a weight increase. Conversely, when walking in the opposite direction, he will experience a weight decrease. The walking speed v necessary to change body weight by a factor n is
$$v = \omega R(\sqrt{n}-1)$$
in the direction of rotation, and
$$v = \omega R(1 - 1/\sqrt{n})$$
counter to the direction of rotation. (ω is the angular velocity and R the radius of rotation at the walking level.) The sensation is one of walking uphill or downhill, depending on the direction of astronaut motion relative to the direction of vehicle rotation. The magnitude of the apparent slope depends on the speed of motion.

3. Progressive changes in body-posture will be experienced when walking along the periphery of rotation. Local uprights

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* This effect could be quite significant. For example, if h/R is 0.66, 0.78 or 0.87, then d is $\pi R/2$, πR or $2\pi R$, respectively.

will be inclined relative to each other by an angle

$$\Theta = 2 \sin^{-1} \left(\frac{\ell}{2R}\right)$$

when separated by a chord ℓ measured on the same circumference R. As a result, visual and gravitoreceptive sensors will provide conflicting signals. These signals will arise regardless of whether the floor along the periphery of the rotating vehicle is kept flat or curved.

4. Rotation is always accompanied by the phenomenon of gravity gradient. For an astronaut standing upright, the difference between head and feet acceleration is

$$\Delta g = \omega^2 h$$

where h is the height of the astronaut.

5. In a rotating system, Coriolis accelerations are produced by motion relative to that system. These accelerations are described by the vector equation

$$\vec{\alpha}_c = -2\vec{\omega}\times\vec{v}$$

where v is the velocity of motion. The Coriolis acceleration is tangential when the velocity is radial, radial when the velocity is tangential, and zero when the velocity is parallel to the spin axis. Coriolis forces affect manual tasks since linear body movements tend to become curvilinear. They can also stimulate the semicircular canals of the inner ear when the head is tilted during rotation and cause postural illusions followed by incorrect reflex responses. The severity of this effect depends primarily on rate of rotation, angle of head tilt, rate of tilt and individual susceptibility.

6. Weight changes will be experienced when motion is along the radius of rotation. Body weight will increase with increasing distance from the center of rotation and vice versa. The change in radius ΔR necessary to affect body weight by a factor n is

$$\Delta R = R(n-1)$$

for moving away from the center of rotation, and

$\Delta R = R(1 - 1/n)$

for moving towards the center. During such motions, Coriolis forces are generated and can be expected to interfere with locomotion.

III. INFORMATION NEEDS

Before artificial gravity is adopted as a standard operational procedure in future space systems, its postulated benefits must be both demonstrated and weighted against potential disadvantages.

The centrifugal acceleration produced by a rotating system is $g = \omega^2 R$ allowing optimization among only three parameters: the gravity level (g), the radius of rotation (R) and the angular velocity (ω).

Parabolic subgravity aircraft flights have shown that a gravity level of at least 0.3 g is required for efficient task performance. These studies suggest that while 0.2 g is not acceptable, 0.5 g is not substantially superior to 0.3 g. Thus, 0.3 g appears suitable for habitability.

An issue not agreed upon is at what levels artificial gravity can delay or prevent degradation of the cardiovascular and musculoskeletal systems. Similarly, it is not presently known to what extent the otolith organs, which specialize in the sensory perception of weight, require gravity stimuli for remaining functional. Anecdotal evidence from Gemini flights indicates an exaggerated otolith sensitivity to acceleration at retrofire and during reentry. Physical exercise and movement about a large enough spacecraft could provide sufficient vestibular stimulation to prevent functional degradation of these organs.

From a physiological standpoint, no demands are imposed on the radius of rotation per se, except only as dictated by suitable combinations of gravity levels and angular velocities. However, habitability requirements (adequate vehicle size) argue for an increase in radius size while engineering (structural) considerations argue for a decrease.

Normal head motions and/or body movements in a rotating environment can generate abnormal Coriolis stimulation of the semicircular canals (the body's sensors of angular acceleration) leading to motion sickness and performance degradation. Under otherwise identical conditions, the severity of the invoked symptoms increases with increasing angular velocity. Ground based studies indicate that nominal head movements of about 230°/sec are tolerable if vehicle rotation is limited below 6 rpm.

In GT-8 high rotation rates were accidentally produced and disruptive effects during head tilts were experienced. However, the relative high angular velocity and the anecdotal nature of the physiological responses preclude meaningful application of this knowledge. Conversely, the gravity levels maintained during the tethered rotation of GT-12 were far below the useful ceiling for any conclusions to be drawn.

Preliminary tolerable limits for acceptable human performance are indicated in Figure 1. Research activities required to optimize these limits include:

1. Work task efficiency tests in orbital flight as a function of g level (confirmatory studies).

2. Evaluation of the preventive or remedial value of artificial gravity on the cardiovascular and musculoskeletal systems as a function of g level or frequency of g exposure:
   a. During prolonged bed-rest (exploratory ground-based studies).
   b. During prolonged weightlessness (inflight confirmatory studies).

3. Inflight otolith sensitivity tests (exploratory studies).

4. Determination of angular velocity limits:
   a. Tolerable (ongoing exploratory ground centrifuge studies).
   b. Optimal (inflight confirmatory studies).

5. Inflight rotational habituation tests as a function of g level or frequency of g exposure (confirmatory studies).

6. Inflight determination of vestibular stimulation thresholds as affected by rotational instabilities (exploratory studies).

These research activities should be carried out in a hierarchical manner, with emphasis being given first to the delineation of zero gravity effects and then to the evaluation of artificial gravity modes or substitutes.

ACKNOWLEDGMENT

Parts of this memo benefitted materially from information available in the MSC document, "A Biomedical Program for Extended Space Missions," now in final preparation by the Directorate of Medical Research and Operations. However, responsibility for views expressed here rests solely with the author. Copies of this memo are transmitted to NASA/MM and MSC/DA for review and comments.

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A. N. Kontaratos

Attachment
Figure 1

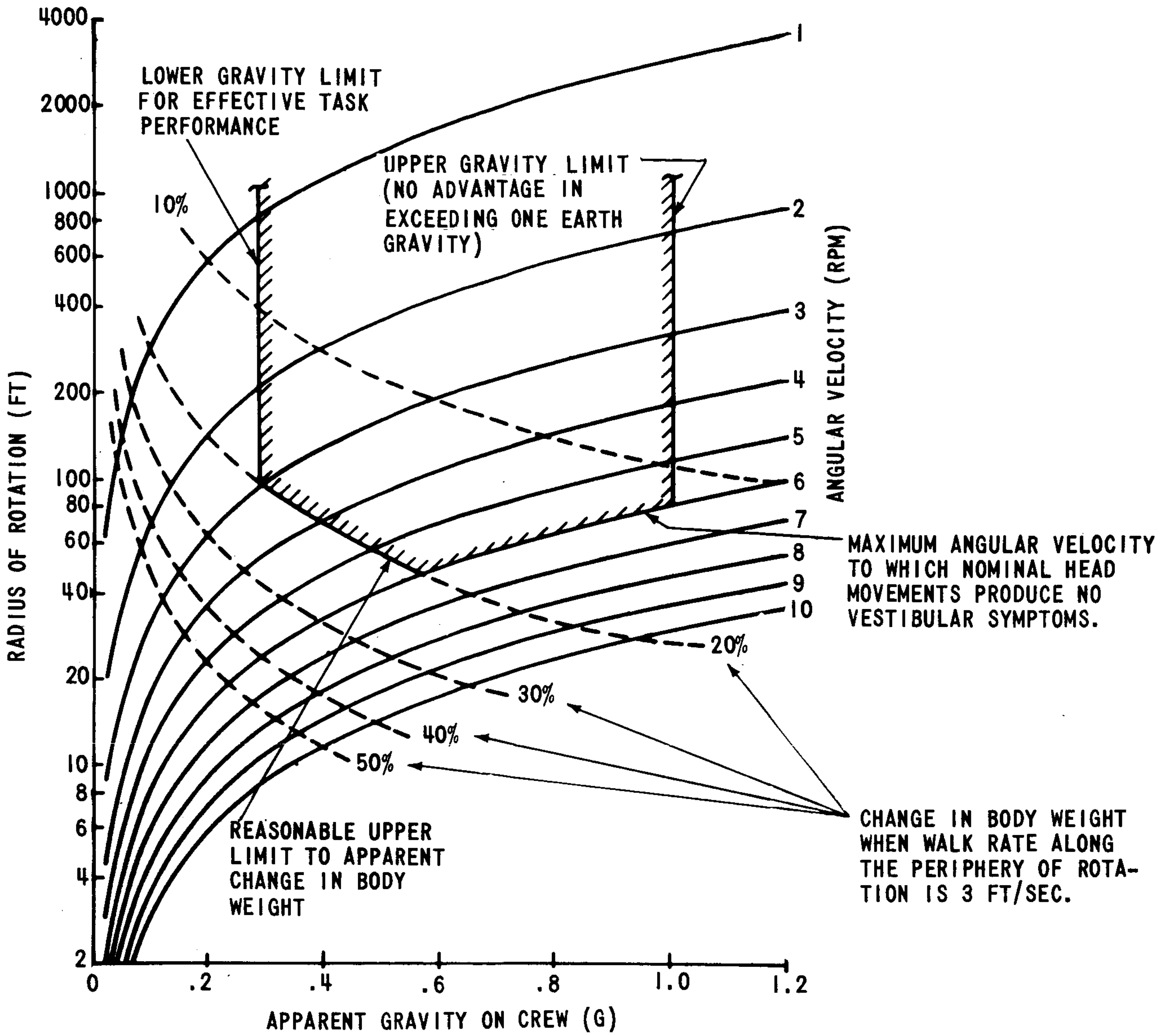

FIGURE 1 - PRELIMINARY TOLERABLE LIMITS FOR ACCEPTABLE HUMAN PERFOFMANCE IN ROTATING SPACE SYSTEMS

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